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A TWO SPACECRAFT TEST OF A SINGLE SPACECRAFT METHOD OF ESTIMATING SHOCK NORMALS

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A TWO SPACECRAFT TEST OF A SINGLE SPACECRAFT METHOD OF ESTIMATING SHOCK NORMALS

by

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Abstract

By assuming the validity of a subset of the Rankine-Hugoniot conservation relations for interplanetary (IP) shocks in an isotropic medium it has been demonstrated, in principle, that improved shock normals can be calculated by using a least squares technique on combined magnetic field and plasma data from a single spacecraft. The scheme devised by Lepping and Argentiero (1971) uses those six conservation relations not involving pressure and temperature. This paper deals with a test of the scheme by examining in detail a shock across which the magnetic field changed direction by a small amount ($\approx 10^{o}$). On January 26, 1968 at about 1430 U.T. this shock was observed by the plasma and magnetic field instruments on Explorers 33 and 35. The spacecraft were 76.6 and 56.9 earth radii (R_E) sunward of the earth respectively (and 43.5 R_E from each other), and therefore well outside the earth's bow shock region, a necessary condition for a valid test. It was assumed that an IP shock's surface is locally plane over dimensions of about 100 R_E. Using this assumption and the known geometrical configuration of the positions of the spacecraft with respect to the earth at the times of the shock onset the orientation of an "observed" normal was ascertained. For comparison least squares best-estimate normals were then calculated for each spacecraft using three different time intervals of data in each case: 9, 12, and 18 minutes, before and after onset. This was repeated using only the magnetic field data and the conventional coplanarity theorem for further comparison. For the 18 minute data interval it was shown that the best-estimate normals for Explorers 33 and 35 agree with each other within less than 3^{o}, and correspond to the "observed" normal within its angular uncertainty due to the time uncertainty of the earth's sudden commencement.

Introduction

The purpose of this paper is to test a single spacecraft method of estimating shock normals by cross checking the results of the method applied independently to the data of two interplanetary spacecraft located about 44 earth radii (R_E) from each other. The method, devised by Lepping and Argentiero (1971), uses a six equation subset of the eight equation Rankine-Hugoniot conservation relations for interplanetary (IP) shocks in an isotropic medium, i.e., those equations not involving temperature or pressure. They showed in principle that improved normals can be calculated by employing a least squares technique to best fit the combined magnetic field and plasma data from a single spacecraft to three equations of the six equation subset, after transformation to an arbitrary frame of reference. The remaining three equations are used explicitly to obtain the direction of the normal and, provided the average pre-shock plasma velocity is sufficiently accurate, the speed of the shock. The reasons for ignoring the equations containing temperature or pressure are:

1. The proton data for these parameters usually show the poorest approximation to a step function of all the shock parameters,
2. Use of these parameters would require electron data which is not always available, and
3. Probably most importantly, use of the energy flux equation, which does not take into account possible heat flow across the shock front (Hundhausen and Montgomery, 1971), is of questionable validity.

Observations and Discussion

This paper deals in detail with a shock whose associated magnetic field changed direction by a small angle ($\approx 10^{o}$) across the shock transition zone.

On January 26, 1968 at about 1430 U.T. this shock was observed by Explorers 33 and 35 with an 88.8 $\pm$ 3.6 sec. time delay between them (see Figure 1). At about 1441 U.T. a sudden commencement was observed on earth. Approximately two hours later (1634 U.T.) Pioneer 8, located about 570 R_E behind the earth near the earth's tail, saw the shock after some deflection of its normal's direction. Notice that the IP shock normal was southward by 20^o but at the Pioneer location it had become northward by $\approx 35^o$ (95% certainty error cone angle is 17^o). Only Explorer 33 was significantly out of the ecliptic plane and was 26 R_E below it. The IP shock normal, $\hat{n}$, was almost perpendicular ($\approx 70^o$) to the preshock magnetic field direction, $\hat{B}_1$. Therefore, little change of direction of the magnetic field would be expected as the shock passed the two spacecraft. The quantities $\hat{n}$ and $\hat{B}_1$ are best fit values, whose estimates will be discussed below.

Figure 2 shows superimposed magnetic field data from Explorers 33 and 35 around the time of the shock. There was essentially no change in θ across the shock surface and only about 10^o change in ϕ. The horizontal lines represent the average of the two individual Explorer 33 and 35 best estimate values. The length of these lines indicate the 18 minute time intervals, before and after shock onset, that were used in the best fit calculation. All six best fit magnetic field parameters seem to have reasonable values when compared to straightforward averages allowing for deviations equal to the rms deviations for each. Notice the occurrence of a periodic structure before and especially after the shock. Behind the shock the oscillations, occurring over about 30 minutes or so, are clearly out of phase between the Explorer 33 and 35 observations.

Figure 3 shows the plasma data also superimposed from Explorer 33 and 35 observations. The horizontal lines in the pre-shock case are simply averages of the dual spacecraft data. However, plasma velocity <u>differences</u> are obtained from the best fit scheme and these along with the added pre-shock averages yield the post-shock "best-fit" values shown. Again the lines represent an 18 minute interval before and after the shock. Notice that the periodic structure after the shock, which was rather clear in the magnetic field data, also appears here except the wave-like signature is not now quite as well defined.

Table 1 gives the best estimate values of the IP shock parameters for the two spacecraft and average values of these best estimates. The subscripts 1 and 2 refer to pre- and post-shock, respectively, and the R-T-N coordinate system, centered at the spacecraft of interest, refers to the unit vectors: $\hat{R}$, radially away from the sun in the ecliptic plane; $\hat{T}$, perpendicular to $\hat{R}$ and lying in the ecliptic such that $\hat{R} \times \hat{T} = \hat{N}$ is normal to the ecliptic and "northward". $\vec{W} = (W_R, W_T, W_N)$ is the plasma bulk velocity difference $\vec{V}_2 - \vec{V}_1$. The N's are the number densities and n_R, n_T and n_N are the components of the shock unit normal. The Alfven mach numbers for pre-and post-shock were 8.5 and 5.5, respectively; these compare well with those of previously studied IP shocks (Hundhausen, 1970). The best estimate Explorer 33 and 35 normals (calculated from the 18 minute interval) differed by less than 3^o. The associated calculated shock speeds were 507 km/sec and 520 km/sec respectively, giving an average value of 513 km/sec. An average pre-shock plasma bulk velocity $\vec{V}_1 = (426, 17.4, -7.0)$ km/sec from the data of both spacecraft was used.

TABLE 1

January 26, 1968 Shock Parameters

Best Estimate Values for the 18 Minute Interval

Parameter	Best Estimate (B.E.) Value Exp. 33	Exp. 35	Average of B.E. for Exps. 33 and 35
B_{1R} (γ)	-1.59	-0.24	-0.92
B_{1T}	-3.16	-3.07	-3.12
B_{1N}	-3.49	-3.83	-3.66
B_{2R}	-5.15	-3.41	-4.28
B_{2T}	-6.60	-6.09	-6.35
B_{2N}	-7.54	-8.26	-7.90
W_R (km/sec)	78.6	85.6	82.1
W_T	-37.0	-35.0	-36.0
W_N	-28.3	-24.2	-26.3
N_1 (#/cm^3)	4.19	4.45	4.32
N_2	9.67	10.52	10.1
n_R	0.826	0.850	0.838
n_T	-0.440	-0.416	-0.428
n_N	-.352	-0.324	-0.338

Two Spacecraft Test

The best fit IP normal was checked for accuracy by comparing its angular displacement from two fixed and intersecting lines in space. These lines were: first, the segment between Explorers 33 and 35 and, second, that between 33 and the earth; they intersected at 47°. Each of these angles can be calculated in two ways: first, by a straightforward calculation using the best estimate normal; this gives the calculated check-angles, and, second, by assuming, for dimensions of about 100 R_E,

(a) a plane shock front, and

(b) a constant shock speed (513 km/sec) and constant normal;

the latter are the observed check-angles. The calculated and observed check-angles can then be compared.

In the case of the Explorer 33-35 line the observed and calculated angles were 80.5° and 84.1° respectively, giving less than a 4° difference. In the case of the Explorer 33-earth line the observed and calculated angles were 47° and 44° respectively, giving approximately a 3° difference. The sudden commencement (SSC) time at earth was taken to be 1441 U.T., giving an 11 minute delay. If 1440 U.T. is taken as the SSC time, giving a 10 minute delay, the angles become 52° and 44° respectively, an $\approx 8^{\circ}$ difference. Assumptions (a) and (b) for the region from Explorer 33 to the earth, even over the path from the bow shock encounter to the earth, are justified within an angle error of 8° or so, because the shock "effectively spends" only about one tenth of its total 33-earth travel time in this latter region.

The (95% certainty) error cone angle associated with the normal was 7.6° which is consistent with the check-angles, or is perhaps somewhat conservative.

Comparison of Analysis-Intervals

To obtain some understanding of the importance of using the proper time interval around the shock for the shock analysis, other time intervals, as well as the 18 minute interval, were used. Henceforth, the term "best estimate" refers only to a given analysis-interval for a given spacecraft, and not necessarily to the final best estimate of the IP normal. Figure 4 shows, for the three separate input data intervals, estimates of the January IP shock normal, as projected on the R-T plane, for both Explorers 33 and 35. The results of both the average magnetic field method (coplanarity theorem) and the best estimate method (auxiliary use of plasma data) of estimating the IP normal are shown. The latter are represented by either dashed or solid arrows, and the former by dashed or solid lines; dashed indicate Explorer 33 estimates and solid indicate Explorer 35. The following features should be pointed out:

a. There is a large (70^{o}) spread of the average normals but a reasonably narrow (14^{o}) spread of the best estimate normals over the three time intervals.

b. Lengthening the time interval of data around the shock for use in calculating the normal does not necessarily improve the estimate, even within the short range considered here (i.e. up to 18 minutes).

c. For each given time interval the best estimate normals between Explorers 33 and 35 are closer together than the average normals.

d. The 18 minute interval was clearly the "proper" choice of interval giving a few degrees difference between the Explorer 33 and 35 best estimate normals.

Figure 5 corresponds to Figure 4 except now the estimates of the IP normal are projected into the R-N plane. All of the above comments again hold except for statement "c". (However, in statement "a" the spread angle for the average normals becomes 46° but that for the best estimate spread remains 14°).

If one had been satisfied with only 12 minutes ("B"-interval) of data around the shock and had not taken advantage of the available plasma data (or did not have such data) one might have been led into a false sense of certainty about the results because of the relatively good agreement between the results of the two spacecraft for this time interval.

Conclusions

We have accurately estimated an interplanetary shock normal and have shown its direction to be significantly different from the $\hat{R}$-direction both in inclination angle θ and azimuthal angle ϕ ($\theta = -20^{\circ}$, $\phi = 153^{\circ}$); the ecliptic plane projection was approximately along the average magnetic field spiral direction. There was no obvious solar flare associated with this shock. The shock may or may not have originated at the sun but it probably did not start as a spherical front near the sun unless the front was severely distorted over 1 A.U. The periodic structure occurring behind the shock as seen especially in the magnetic field data is no doubt, in part, responsible for the fact, stated above, that lengthening the analysis interval does not necessarily improve the estimate of the normal. A proper analysis-interval is probably one that encompasses, as exactly as possible, two oscillations if such quasi-periodic structure exists after the shock, or at most should be limited to the interval just up to the first obvious discontinuity appearing after the shock.

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FIGURE CAPTIONS

Figure 1 The positions of Explorers 33 and 35 and Pioneer 8, at the time of the January 26, 1968 shock, shown in the ecliptic R-T plane. Also shown are the best fit IP normal, $\hat{n}$, and pre-shock magnetic field direction, $\hat{B}_1$, as well as a roughly estimated normal (using average magnetic fields) at Pioneer 8. Quantities in parenthesis refer to the direction perpendicular to the ecliptic plane in either degrees or R_E. The question mark (?) at Pioneer 8 refers to the large uncertainty (error cone 17^o) of the normal's estimate at that location.

Figure 2 Superimposed magnetic field data for Explorers 33 and 35. F is the magnitude, ϕ is the azimuthal angle measured counterclockwise in the ecliptic plane from $\phi = 0^o$ in the direction of the sun, and θ is the angle of inclination measured positive northward from the ecliptic.

Figure 3 Superimposed plasma data for Explorers 33 and 35. W is the thermal speed and V is the magnitude of the bulk plasma velocity, whose direction is designated by θ (same as in Figure 1) and ϕ ($\phi = 0^o$ in antisolar direction). N is the plasma number density.

Figure 4 Estimates of the January 26, 1968 shock normal from Explorers 33 and 35 data and projected into the R-T plane. Both average-field and best-fit methods are shown, each for three separate data intervals.

Figure 5 Estimates of the January 26, 1968 shock normal from Explorers 33 and 35 data and projected into the R-N plane.

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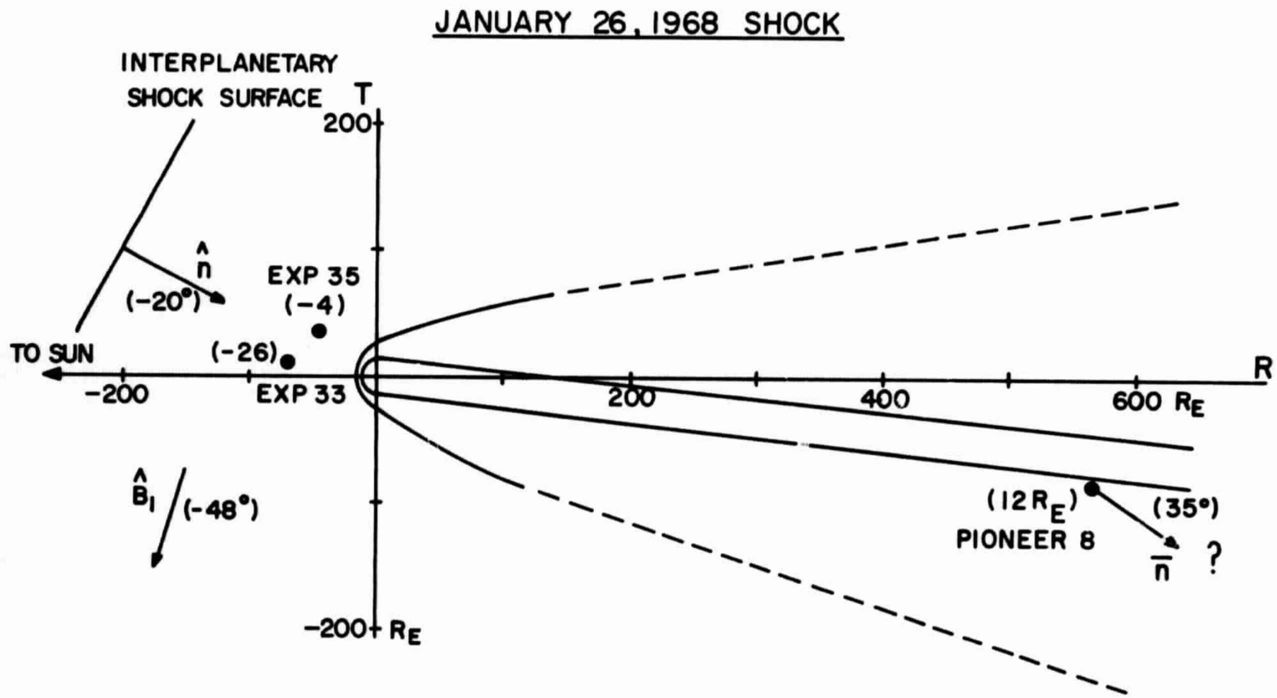
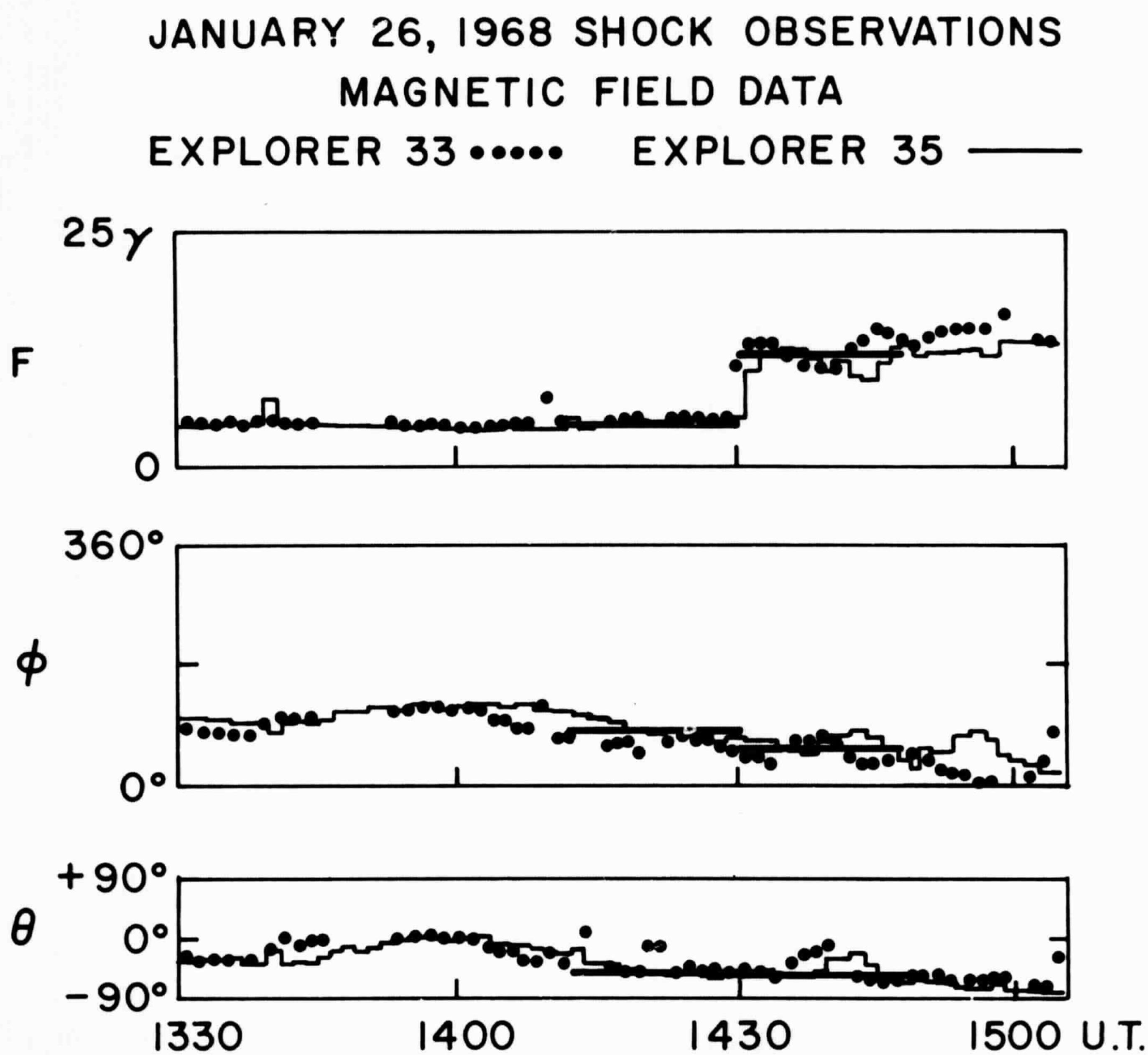


JANUARY 26, 1968 SHOCK
INTERPLANETARY
SHOCK SURFACE
T
200
$\hat{n}$
(-20°)
EXP 35
(-4)
(-26)
TO SUN
-200
EXP 33
200
400
600 R_E
R
$\hat{B}_I$
(-48°)
($12 R_E$)
(35°)
PIONEER 8
$\bar{n}$
?
-200 R_E

Figure 1



JANUARY 26, 1968 SHOCK OBSERVATIONS
MAGNETIC FIELD DATA
EXPLORER 33 •••••
EXPLORER 35 ——
F
25γ
0
φ
360°
0°
θ
+90°
0°
-90°
1330
1400
1430
1500 U.T.

Figure 2

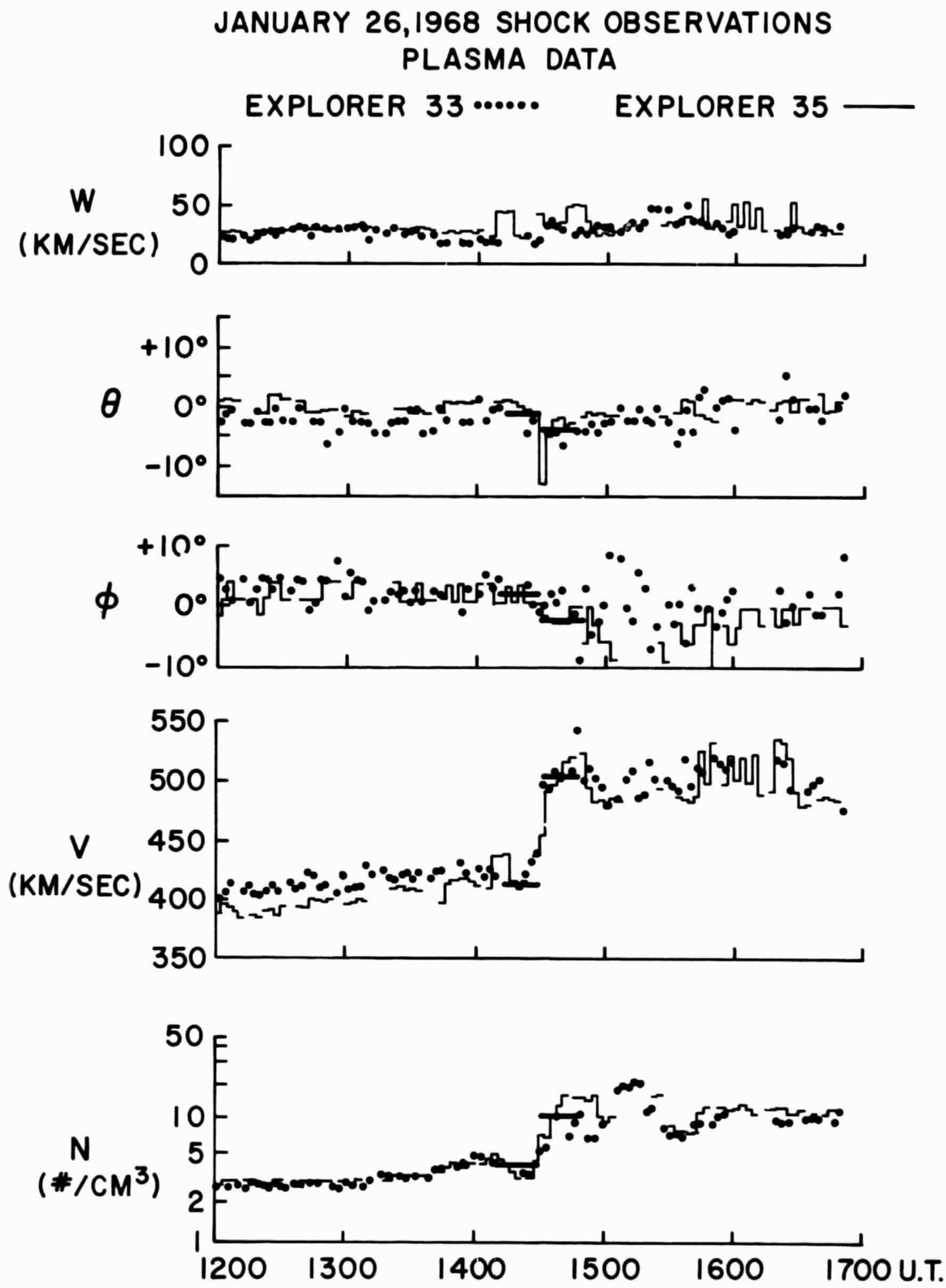
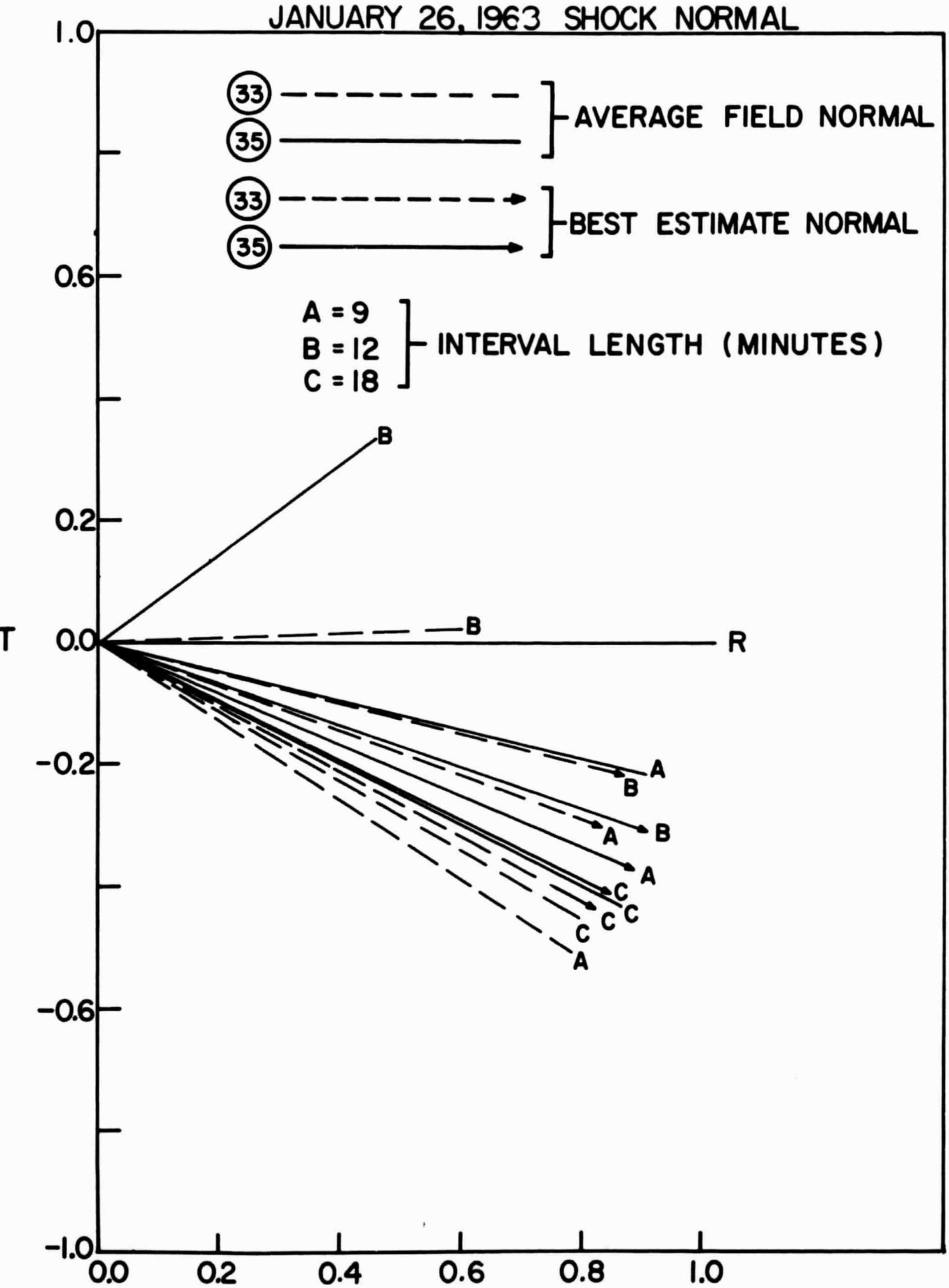
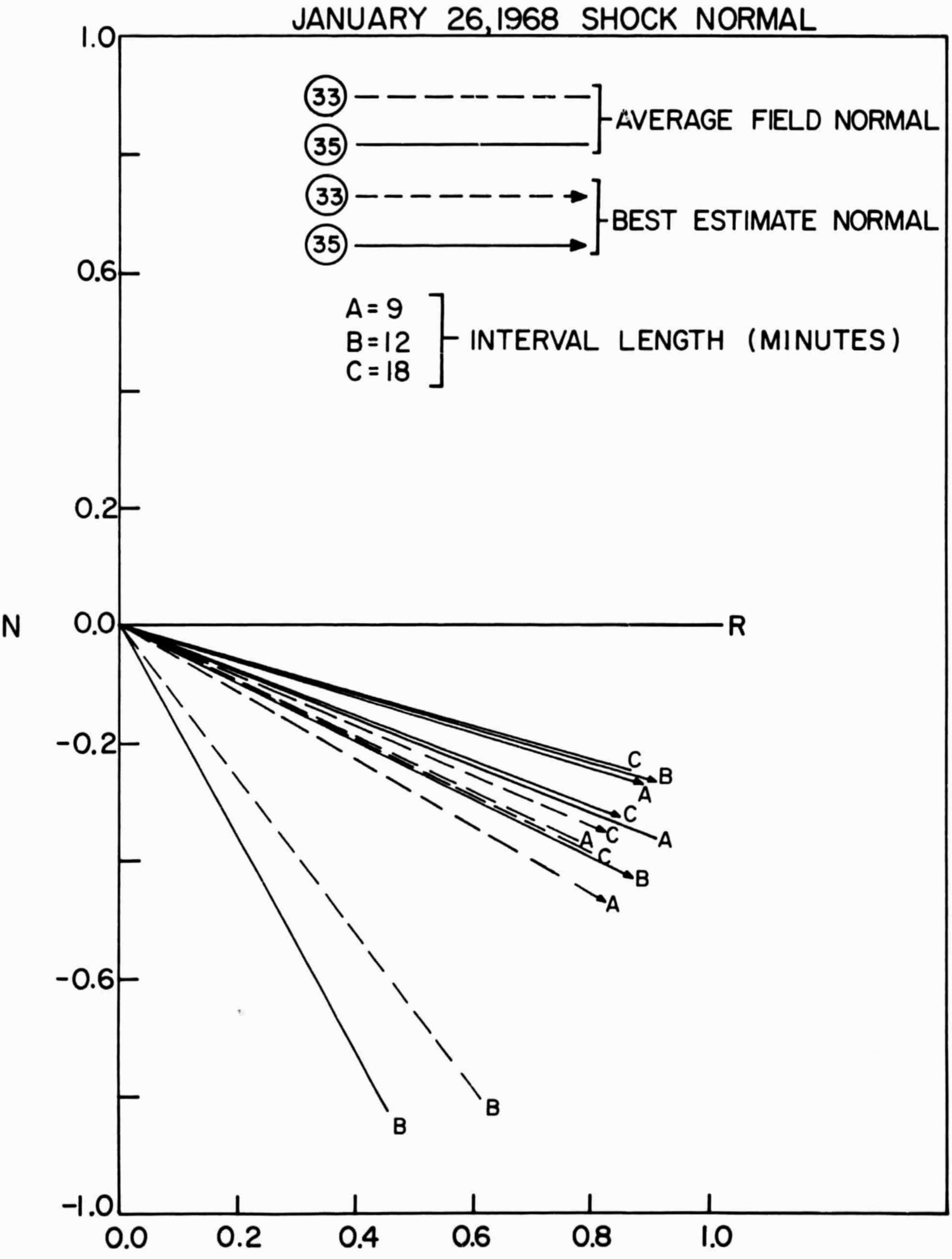

JANUARY 26,1968 SHOCK OBSERVATIONS
PLASMA DATA
EXPLORER 33 ······
EXPLORER 35 ——
W
(KM/SEC)
100
50
0
θ
+10°
0°
-10°
φ
+10°
0°
-10°
V
(KM/SEC)
550
500
450
400
350
N
(#/CM³)
50
10
5
2
1
1200
1300
1400
1500
1600
1700 U.T.

Figure 3



JANUARY 26, 1963 SHOCK NORMAL
33
35
AVERAGE FIELD NORMAL
33
35
BEST ESTIMATE NORMAL
A = 9
B = 12
C = 18
INTERVAL LENGTH (MINUTES)
T
R
1.0
0.6
0.2
0.0
-0.2
-0.6
-1.0
0.0
0.2
0.4
0.6
0.8
1.0

Figure 4



JANUARY 26, 1968 SHOCK NORMAL
33
35
AVERAGE FIELD NORMAL
33
35
BEST ESTIMATE NORMAL
A = 9
B = 12
C = 18
INTERVAL LENGTH (MINUTES)
1.0
0.6
0.2
0.0
-0.2
-0.6
-1.0
N
R
0.0
0.2
0.4
0.6
0.8
1.0

Figure 5